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Establishment of Pigging Model for CO_2 Long-distance Pipeline Pigging Devices and Research on Pigging Performance

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Abstract

CO_2 pipeline transportation is a key link in the development of carbon capture, utilization and storage (CCUS) technology. Due to the presence of impurities in the gas source and the special transportation conditions, hydrates are prone to form during the pipeline transportation of CO_2. Therefore, pigging operations need to be carried out to ensure the safe and smooth operation of the pipeline. Based on the CO_2 pipeline pigging parameters in the carbon capture and storage process of Kingsnorth, a pigging numerical model with the help of the pigging theory and pigging module of OLGA software was constructed in this study. The model verification results show that under the basic and full transportation volume conditions, the relative errors of the simulated values and the on-site detection values of the pigging time of the supercritical/dense-phase CO_2 pipeline and the pigging speed at the pipeline outlet are 4.20%, 4.17%, 3.17%, and 3.86% respectively, all within the acceptable range of the project. Based on this model, a simulation study was conducted on the pigging work of a certain supercritical CO_2 long-distance pipeline. The results show that the pigging effect of the intelligent pigging device is superior to that of the polyurethane mechanical pigging device. The pipeline pigging model established in this research can accurately predict the pigging performance of CO_2 long-distance pipelines, providing a research method and guidance for the optimization of CO_2 pigging devices.

Keywords

CO_2 Pipeline Transportation; Hydrate; Pigging Model; Pigging Device.

1. INTRODUCTION

In the crucial global process of actively moving towards a low-carbon economy, carbon capture, utilization and storage technologies, with their outstanding emission reduction efficiency, have become the most efficient means of CO_2 reduction in the world at present, playing a pivotal role in this major transformation [1]. CO_2 transportation, as the core link for the complete realization of CCUS technology, has a decisive impact on the implementation of the entire CO_2 reduction strategy [2]. Its main transportation methods include tank truck transportation, pipeline transportation, and sea transportation [3]. Among them, pipeline transportation is more economical and reliable compared to the other two transportation methods, which makes it the main way for long-distance land transportation of CO_2 in CCUS projects at home and abroad [4].

CO_2 pipeline transportation can be carried out in gaseous, liquid, supercritical/dense phase forms. The three phase forms of transportation are suitable for different working conditions. Due to the critical temperature of CO_2 being 31.4℃, long-distance pipelines are prone to crossing the critical temperature during normal transportation, causing phase changes.

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Moreover, the CO_2 gas source itself contains impurities, so the formation of hydrates is inevitable [5]. Therefore, in order not to affect the normal transportation of the CO_2 pipeline, it is necessary to clear the CO_2 pipeline. Most of the time, a pigging device is used for pigging to ensure that the CO_2 is dehydrated during commissioning and pigging, and to remove the accumulated hydrates in the pipeline, thereby improving the transportation efficiency.

In recent years, scholars at home and abroad have also begun to pay attention to the pigging devices used in CO_2 pipeline pigging. Lima [6] et al. demonstrated through short-distance pipeline pigging experiments that the parameter crucial for pigging device auxiliary leakage detection, namely the pigging device speed, can be determined by commonly used monitoring parameters. Their research utilized pipeline pressure sensors and monitoring data to determine the speed of the pigging device, and then compared the pigging effects under different pigging device speeds. Ramsen [7] et al. conducted a study on the pigging operation of a CO_2 pipeline over 200 kilometers long in the Bamus Oil and Gas field CCS project. Under dense-phase conditions, they used OLGA software to simulate the operating speed and time of the pigging device. The results show that the operation of the pigging device requires a speed between 0.5 m/s and 3m/s to prevent the pigging device from getting stuck in the pipeline or being damaged due to excessive speed. A research team conducted a study on the pigging operations of gas transmission pipelines [8]. In this study, the pigging effect was mainly evaluated by analyzing the running time and traveling distance of the pipeline pig. The team employed the volumetric method in combination with pipeline average pressure correction to calculate the running time and traveling distance of the pig. A comparison between the calculated results and the actual arrival time of the pig at the receiving terminal reveals that the calculation error is merely 5 minutes, which validates the effectiveness of the proposed calculation method.

To sum up, most of the domestic research on pigging technology is focused on oil and gas pipelines, while the related research on pigging of long-distance CO_2 pipelines is still relatively scarce. There are relatively more maintenance and inspection of long-distance CO_2 pipelines abroad, but the focus is mainly on the research and application of new pigging devices and safe pigging operations. No detailed research has been conducted on the removal of accumulated dirt from the pipelines. In addition, the analysis of other factors affecting the pigging effect and the measures to improve the efficiency of pigging operations are still not perfect. For this purpose, this paper took the long-distance CO_2 pipeline as the object, focused on the operation of the pigging device, established a pigging model using OLGA software and verified and analyzed the model. Finally, a simulation study on the pigging of a certain supercritical CO_2 long-distance pipeline was conducted, and pigging suggestions were put forward to achieve safe and efficient pigging.

2. ESTABLISHMENT OF THE CO_2 PIPELINE PIGGING MODEL

In long-distance CO_2 pipelines, the temperature and pressure vary with the transportation distance, and CO_2 is prone to form hydrates with free water and impurities. Although European research institutions recommend that the moisture content of the gas source be controlled within 500ppm, the formation of hydrates is inevitable due to the cost of capture and dehydration as well as the condensation caused by temperature drop during transportation. Hydrates can cause gas-solid two-phase flow and erode the pipe wall. After accumulation, they can easily reduce the transportation efficiency and even clog the pipeline. It is necessary to predict through the hydrate phase equilibrium curve to determine the formation location and time of hydrates. For sections that need to be cleaned, pigging equipment should be used for pigging. As many scholars have studied the determination of the formation time and location of

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hydrates, this article focuses on the theoretical basis of pipe pigging and the establishment of models.

2.1. Theoretical Basis of Pipeline Pigging

During the pigging operation, the pigging device operates by the thrust generated by the pressurized fluid. The specific principle is to use the pressure of the fluid in the pipeline to drive the pigging device to run, in order to remove the dirt in front of the pigging device. The parameters required during the pigging operation include driving pressure, the amount of water in the pipeline before and after the pigging device, the operating speed of the pigging device, and the time taken to complete the pipeline. When the operating speed of the pigging device is within the range of the CO_2 pipeline pigging operation speed (0.5 to 3m/s), the shorter the pigging time used for the pigging operation, the more stable the operating speed and the more thorough the quality of the hydrates removed, the more ideal the pigging operation effect will be, providing a certain basis for the subsequent judgment of the pigging operation effect.

2.1.1. Frictional Force Acting on the Pigging Device

(1) Static friction force

The static friction force between the pigging device and the pipe wall is F_0. For a static pigging device, the static friction force must be overcome when it starts to move. The pigging device will only move when the pressure difference of the pigging device is large enough.

(2) Pipe wall friction force

The formula for the frictional force exerted by the pig on the pipe wall due to their contact is as follows:

$$F_w = max\left(0, F_0 - f_w\left|U_p\right|\right) \cdot sgn\left(U_p\right) \tag{1}$$

Where, F_0 is the static friction force, N, f_w represents the tube wall friction coefficient, Ns/m, U_p is the pipeline pigging device speed, m/s.

As the speed U_p of the pig increases, the contact between the pig and the pipe wall decreases, and the friction between the pig and the pipe wall also reduces. This effect can be approximately represented by the wall friction coefficient.

(3) Viscous friction force

When the pig moves, the fluid film around the pig causes viscous friction. This friction is calculated using the following formula.

$$F_\mu = f_1 U_p + f_2 U_p\left|U_p\right| \tag{2}$$

Where, c is the linear friction coefficient, Ns/m, f_2 stands for the second friction coefficient, Ns^2/m^2.

2.1.2. Leakage During Pipeline Pigging Operations

There are two different types of leaks during the pigging operation. For the subsequent simulation, the leakage during the operation of the pig is characterized by changing the gap between the pig and the pipe wall.

(1) Leakage caused by pressure drop

Due to the pressure drop on the pig, the liquid can be pushed from the rear of the pig to the front. The pressure drop caused by the volume flow rate is given by the following formula:

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$$U_{p1} = \left(c_{p1} \cdot \sqrt{\frac{\Delta P_{\text{pig}}}{\rho}}\right) \cdot sgn\left(\Delta P_{\text{pig}}\right) \tag{3}$$

In which, c_{p1} represents the leakage coefficient, ΔP_{pig} stands for the pressure drop on the pig, N/m^2, and ρ is the working medium density, kg/m^3

(2) Leakage caused by sliding (reverse leakage)

Due to the sliding between the pig and the surrounding fluid, some of the fluid in front of the pig will not be carried away by the pig but will leak between the pig and the pipe wall. When the gap between the pig and the pipe wall is very narrow, when calculating the flow rate of the fluid film passing through the pig, the effects of gravity and pressure gradient can be ignored.

Assuming laminar flow velocity $v_f = \frac{U_p}{2}$, The average velocity of the fluid is:

$$Q_{\text{fl}} = \frac{\pi\left(D^2 - D_p^2\right)}{4} v_f \tag{4}$$

Where, D and D_{p} are the inner diameter and outer diameter of the pipe of the pig, respectively, m.

2.1.3. Pipeline Pigging Calculation Equation

The OLGA software was used to simulate the pigging process of long-distance CO_2 pipelines in this manuscript. Since there are water hydrates and CO_2 media in the pipeline, which are not a single substance, a two-fluid model is selected in the simulation. This model can more accurately reproduce the pigging process and provide data support for evaluating the pigging effect. The basic mathematical equations of the two-fluid model mainly consist of the mass conservation equation, the momentum conservation equation, and the energy conservation equation [11]. The formulas are as follows:

(1) Mass conservation equation

Gas phase mass conservation equation:

$$\frac{\partial}{\partial t}\left(V_g \rho_g\right) = -\frac{1}{A}\frac{\partial}{\partial z}\left(A V_g \rho_g v_g\right) + \psi_g + G_g \tag{5}$$

Wall surface liquid phase mass conservation equation:

$$\frac{\partial}{\partial t}\left(V_L \rho_L\right) = -\frac{1}{A}\frac{\partial}{\partial z}\left(A V_L \rho_L v_L\right) + \psi_g \frac{V_L}{V_L + V_D} - \psi_e + \psi_D + G_L \tag{6}$$

Droplet mass conservation equation:

$$\frac{\partial}{\partial t}\left(V_D \rho_L\right) = -\frac{1}{A}\frac{\partial}{\partial z}\left(A V_L \rho_L v_D\right) + \psi_g \frac{V_D}{V_L + V_D} - \psi_e + \psi_D + G_D \tag{7}$$

In which, t represents Calculate the time, s. ∂ stands for the differential of space. V_g, V_L, V_D respectively represent the volume fractions of the gas phase, liquid film, and liquid droplet phases. ρ_g, ρ_L, ρ_D respectively represent the densities of the gas phase, liquid film, and liquid droplet phases, kg·m^{-3}. A represents the cross-sectional area of the pipeline's flow passage, m^2. v_g, v_L, v_D respectively represent Different phase transmission speeds, m·s^{-1}.ψ represents the inter-phase mass transfer occurring within the quality unit, kg·m^{-3}. G_g, G_L, G_D respectively represent the given different phase state mass sources, kg·m^{-3}.

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(2) Momentum conservation equation

Gas-phase and droplet momentum conservation equations:

$$\frac{\partial}{\partial t}\left(V_g\rho_g v_g + V_D\rho_L v_D\right) = -\frac{1}{A}\frac{\partial}{\partial z}\left(AV_g\rho_g {v_g}^2 + AV_D\rho_L {v_D}^2\right) - \left(v_g + v_D\right)\frac{\partial p}{\partial z} + \psi_g\frac{V_L}{V_D} - \frac{1}{2}\lambda_g\rho_g|v_g|v_g\frac{S_g}{4A} - \frac{1}{2}\lambda_i\rho_g|v_r|v_r\frac{S_i}{4A} + \left(V_g\rho_g + V_L\rho_L\right)g\cos\alpha + \psi_e v_i - \psi_D V_D \tag{8}$$

For the liquid film, the following momentum conservation equation is satisfied:

$$\frac{\partial}{\partial t}\left(V_L\rho_L v_L\right) = -\frac{1}{A}\frac{\partial}{\partial z}\left(AV_L\rho_L v_L^2\right) - V_L\frac{\partial p}{\partial z} - \frac{1}{2}\lambda_L\rho_L|v_L|v_L\frac{S_g}{4A} + \frac{1}{2}\lambda_i\rho_g|v_r|v_r\frac{S_i}{4A} + V_L\rho_L g\cos\alpha - \psi_g\frac{V_L}{V_L+V_D}v_\alpha - \psi_e v_i + \psi_D V_D - V_L\left(\rho_L - \rho_g\right)g\frac{\partial V_L}{\partial z}\sin\alpha \tag{9}$$

In which, v_r represents Relative speed, m/s. α represents the angle between the pipeline axis and the vertical line. i represents the interface between the gas-liquid two-phase main body. S_g, S_L, S_D respectively represent the respective interfacial wetting areas between the gas phase, liquid film, and gas-liquid two-phase mixture, m; When the liquid film evaporates, for example, $\psi_g > 0$, Then, $v_\alpha = v_L$. When the droplet evaporates, for example, $\psi_g < 0$, Then, $v_\alpha = v_D$. When the gas phase condenses, for example, $\psi_g < 0$, Then, $v_\alpha = v_L$.

(3) Energy conservation equation

Regarding the conservation equation for gas-liquid mixtures:

$$\left[m_g\left(E_g + \frac{1}{2}{v_g}^2 + gh\right) + m_L\left(E_L + \frac{1}{2}{v_L}^2 + gh\right)\right] + m_D\left(E_D + \frac{1}{2}{v_D}^2 + gh\right) = H_S + U$$
$$-\frac{\partial}{\partial z}\left[m_g v_g\left(H_g + \frac{1}{2}{v_g}^2 + gh\right) + m_L v_L\left(H_L + \frac{1}{2}{v_L}^2 + gh\right) + m_D v_D\left(H_D + \frac{1}{2}{v_D}^2 + gh\right)\right] \tag{10}$$

In which, E represents the unit mass internal energy of each phase, J/kg. H represents elevation, m. H_S represents the enthalpy of the quality source, J. U represents heat transfer through the pipe wall, J. m_g, m_L, m_d respectively represent the unit mass of the gas phase, liquid film, and liquid droplet phases, kg.

2.2. Establishment of the Pigging Model for Long-Distance CO_2 Pipelines

Based on the above gas pigging theory foundation and the OLGA calculation equation, using the hydrate model as the initial condition for the pigging simulation process, a CO_2 long-distance pipeline pigging model was established [12]. The specific process of establishing the pigging model is as follows:

(1) By combining the specific pipeline project parameters, the CO_2 long-distance pipeline hydrate generation model was established using the OLGA software [13].

(2) On the pipeline FLOWPATH in the above OLGA software established CO_2 hydrate model, the FA-MODELS-PIG module was added.

(3) Set the pigging sending time (INSERTTIME).

(4) Set the receiving and sending positions (LAUNCHPOSITION, TRAPPOSITION) respectively.

(5) The sending LAUNCH is set near the pipeline inlet, and the receiving TRAP is set near the pipeline outlet.

(6) The pigging attributes are set as follows: Different types of pigging devices have different attributes, mainly reflected in the setting of the pigging device's mass and bypass rate, mainly

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including attributes such as MASS (on-site pigging device mass), WALLFRICTION (friction coefficient between the pigging device and the inner wall of the pipeline), and STAEICFORCE (maximum static friction force); other dynamic parameters can be set according to default values.

(7) During the operation of the pigging device in the CO_2 long-distance pipeline, the key data that need to be monitored include: UPIG and ZZPIG (pigging device speed and running distance), PT and TM (pressure and temperature along the pipeline), the cumulative amount of hydrate in the pipeline before the pigging operation, and the cumulative amount of hydrate removed, etc.

3. VALIDATION OF THE PIPELINE PIGGING MODEL

To verify the feasibility of the pigging model for long-distance CO_2 pipelines, the pigging parameters of the CO_2 pipeline during the carbon capture and storage process in Kingsnorth [14] were compared with the simulation values. The pigging model of Kingsnorth established by the pigging module in the OLGA software is shown in Figure 1.

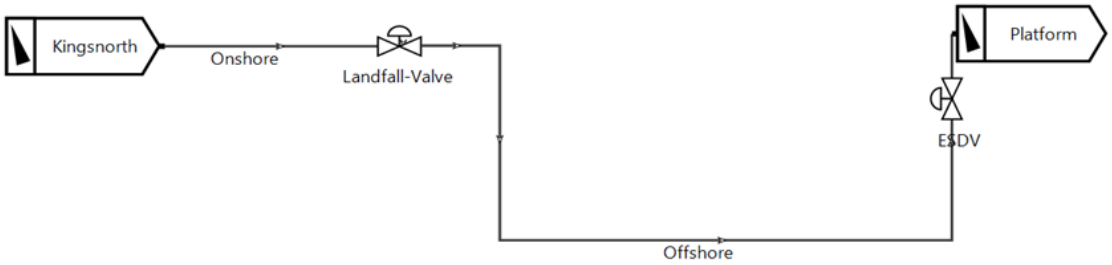
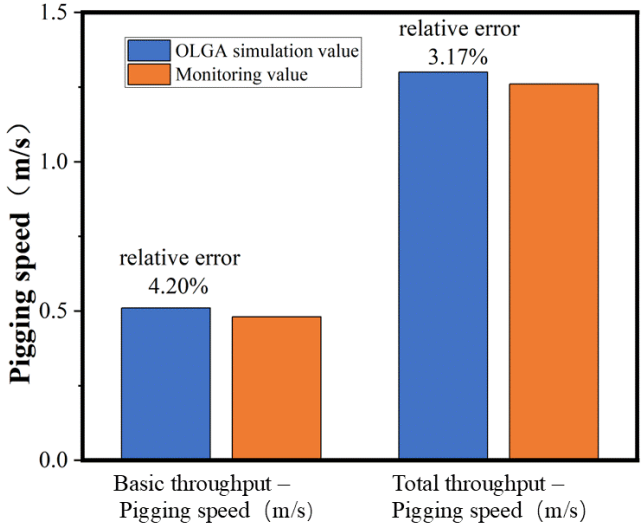


Figure 1. Kingsnorth Pipeline OLGA pigging model

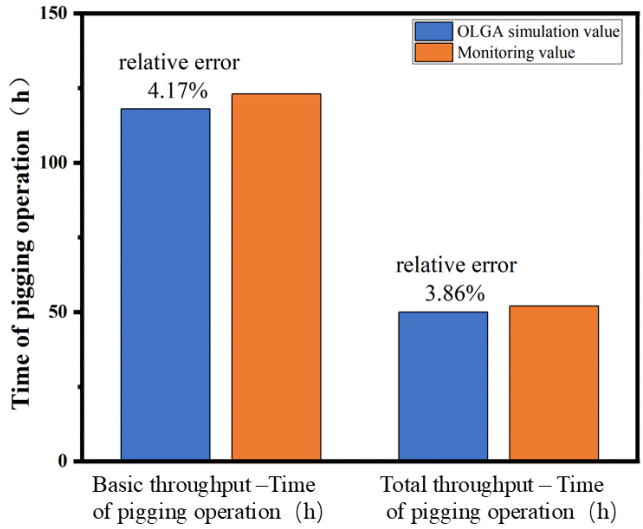
The total length of this CO_2 pipeline is 277 kilometers, including 7 kilometers of the onshore section and 270 kilometers of the underwater pipeline. The pipe diameter is 914 mm. Under the basic flow rate (6600 t/d) and the full flow rate (26400 t/d), the inlet temperature, inlet pressure and pipe material are as follows: 40 °C, 15 MPa, X80; The basic parameters of the OLGA pigging device, including static force, wall friction force, linear friction force, secondary friction force, pigging device mass, and leakage coefficient, are set as: 1000 N, 1000 N, 10 Ns/m, 0 Ns^2/m^2, 140 kg, and 0.

Based on the data provided by the project, a simplified pipeline topography was input into OLGA. Under the Kingsnorth dense-phase operation condition, the inlet flow rate of CO_2 remained at the normal operating state. The monitoring results were referenced from (Transient Analysis – Pigging (Pipeline), KCP-GNS-FAS-DRP-0006), which used flow meters to monitor the running speed and running time of the pig at the pipeline outlet. During the basic throughput, the running speed of the pig at the pipeline outlet was 0.48 m/s and the running time was 123 hours; during the full throughput, the running speed of the pig at the outlet was 1.26 m/s and the running time was 52 hours. The simulation values and monitoring results of CO_2 pipeline pigging under supercritical/dense-phase conditions are shown in Figure 2.

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a. Pipeline Inspection Rod Speed Comparison Chart



b. Diagram showing the comparison of pig running time

Figure 2. Simulated and monitored values of supercritical/dense-phase CO2 pigging

As shown in Figure 2, in the supercritical/dense-phase CO_2 pipeline transportation, at the basic flow rate, the OLGA simulation value of the pig running speed at the pipeline outlet is 0.03 m/s faster than the monitoring value, with an error percentage of 4.20%; the simulation value of the pig running time is 5 hours faster than the monitoring value, with an error percentage of 4.17%. Since this pig pigging simulation did not consider the pig getting stuck in the pipeline or the certain gap between the pig sealing parts and the pipe wall, etc., this OLGA pigging model simulation speed was slightly greater than the actual monitoring value, and the pigging simulation time was less than the actual monitoring time. Additionally, for the absolute error value of 5 hours, according to the reports of multiple CO_2 pipeline pigging by foreign experts such as Skone [15], when the pigging operation time of the long-distance pipeline exceeds 5 days, the error between the simulated pigging time using the OLGA software and the actual time can be within ±5 hours, which can be used as a reference for pigging reception. Therefore, for the 5-hour pigging time simulated under the basic flow rate of the 277 km pipeline, the error is within the acceptable range.

When transporting CO_2 at full flow rate, driving the pig to clean the pipeline, the OLGA simulation value of the pig running speed at the pipeline outlet is 0.04 m/s faster than the monitoring value, with an error percentage of 3.17%; the simulation value of the pig running

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time is 2 hours faster than the monitoring value, with an error percentage of 3.86%. Since the running speed of the pig in the full flow rate is 1.26 m/s, which is more in line with the reasonable running speed range of 0.5 m/s to 3 m/s for the pig, the simulation results are closer to the actual monitoring results.

Therefore, using the OLGA software to simulate the pigging operation of the CO_2 long-distance pipeline under supercritical/dense-phase conditions, whether it is under the basic flow rate or the full flow rate, the running of the pig is compared with the actual monitoring running speed and running time, the error is small and within a certain range, thereby verifying the accuracy and effectiveness of the CO_2 long-distance pipeline pigging simulation method using the OLGA software, and having certain reference value for accurately receiving the pig using pig catcher within the predetermined time.

4. A STUDY ON THE PIGGING PERFORMANCE OF A LONG-DISTANCE CO_2 PIPELINE

For the pigging operation of the long-distance CO_2 pipeline, due to the influence of the pig type, this chapter adopts an intelligent pig to simulate the pigging performance under supercritical conditions. It analyzes the running speed, running time, and the content of hydrates removed under the corresponding conditions, as well as the changes in pipeline temperature and pressure parameters. The pipeline parameters are selected from a certain oilfield project, with a total length of 42 km, the lowest altitude being 1321m and the highest being 1630m. The terrain parameters are shown in Figure 3.

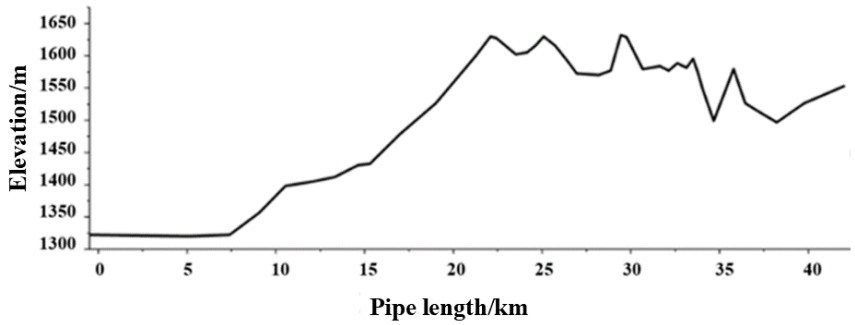


Figure 3. Topographic parameter map of the pipeline

Taking into account the drying characteristics, supercritical properties, and various types of pigging devices of CO_2 in long-distance pipelines, in accordance with the CO_2 pipeline design standards and the selection criteria for pigging devices [16], it was confirmed that the intelligent pigging devices was recommended for the supercritical/dense-phase transportation. Referred to SY/T0533-94 [17], an intelligent pigging device was selected according to the pipeline structural and operating condition parameters with a mass of 200 kg, a maximum wall friction force of 1000 N, a maximum single discharge volume of 158.3 kg, and a leakage coefficient of 0.1. The pigging performance was simulated using the pigging module of the OLGA software, Based on the verified pigging modeling method for CO_2 long-distance pipelines, inputting the basic parameters of the CO_2 pipeline and the basic parameters of the pig, the specific parameters of the pigging operation under the supercritical/dense-phase conditions were obtained, including the pigging running speed, average speed, pigging position, running distance and pipeline temperature and pressure. The pigging effect is analyzed and compared.

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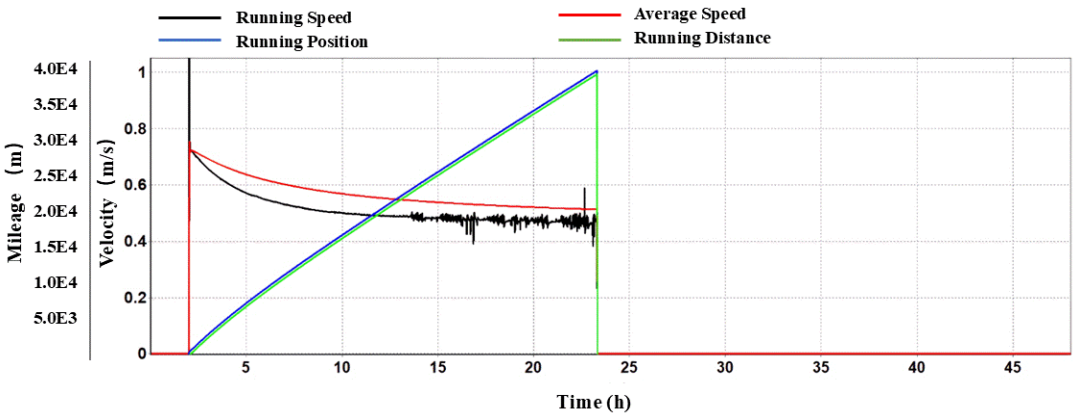


Figure 4. Operating Parameters of the intelligent pigging device

As shown in Figure 4, for the simulation of pipeline pigging with the intelligent pig in the supercritical/dense-phase transportation condition, the pig was launched at 2 hours and was received by the collector at 23 hours. It operated throughout the pipeline for approximately 21 hours. The operating speed of the pig was about 0.5 m/s, and it maintained a relatively stable speed after 15 km.

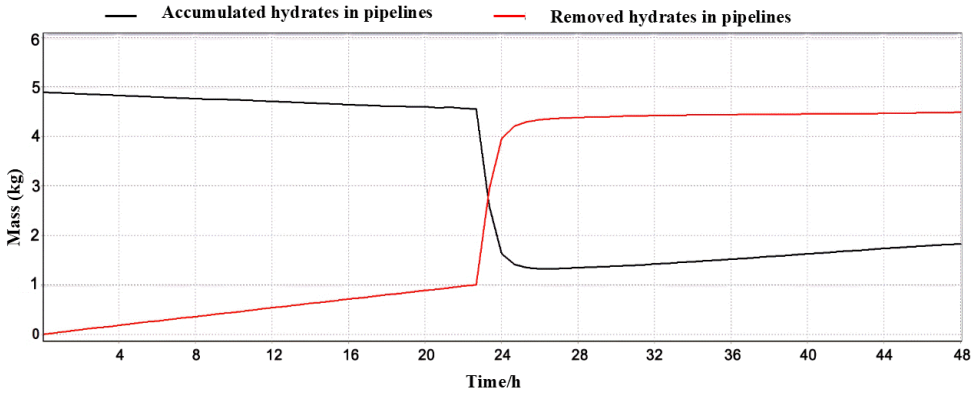


Figure 5. shows the volume of hydrates removed by the intelligent pigging device

As shown in Figure 5, the total amount of hydrate in the pipeline before the pigging operation reached approximately 5 kg. After the intelligent pigging operation, only 1.4 kg remained. The amount of hydrate cleared by the intelligent pigging device in one operation was approximately 3.6 kg.

In conclusion, for CO_2 pipeline transportation of pigging under supercritical/dense-phase conditions, the simulation results show that the intelligent pigging device can perform full-line pigging in the pipeline. The volume of hydrate removed by the intelligent pigging device is 3.6 kg, and the average speed is approximately 0.55 m/s. Furthermore, the intelligent pigging device can simultaneously conduct inspections inside the pipeline. Therefore, this pigging device is particularly recommended for use in supercritical/dense transportation pipelines.

5. CONCLUSIONS

Regarding the problems such as decreased transportation efficiency and pipeline blockage caused by hydrate formation in the CO_2 long-distance pipelines in CCUS system, this study relies on the CO_2 pipeline pigging parameters during the Kingsnorth carbon capture and storage process, and uses the OLGA software to establish a CO_2 long-distance pipeline pigging model. It systematically explores the pigging effects of the intelligent pigs in the supercritical/dense-phase transportation pipeline. The main conclusions are as follows:

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1) This paper uses the OLGA software combined with the parameters of an oilfield project to establish a hydrate formation model for the CO_2 long-distance pipeline, provides relevant pigging theoretical basis and OLGA calculation equations, and uses this hydrate model as the initial condition for the pigging simulation process, establishing a CO_2 long-distance pipeline pigging model.

2) Based on the CO_2 pipeline pigging parameters in the Kingsnorth carbon capture and storage process, using the OLGA software to simulate data analysis and comparison verification reveals that under the basic flow rate and full flow rate two working conditions, the maximum relative errors of the pigging time and the speed of the pigging device at the pipeline outlet in the supercritical / dense-phase CO_2 pipeline simulation results compared with the measured values are 4.20%, 4.17%, 3.17% and 3.86% respectively, all meeting the acceptable error requirements. In summary, using the OLGA software to simulate the pigging operation of the CO_2 long-distance pipeline in the supercritical working condition has certain accuracy and effectiveness.

3) By applying the established CO_2 pipeline pigging operation model, the pigging effect of the intelligent pig in the supercritical/dense-phase state was analyzed. The study shows that in the supercritical CO_2 pipeline pigging process, the running speed of the intelligent pig is approximately 0.55 m/s, and the mass of hydrates removed is 3.6 kg.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES

[1] Yan Y, Borhani T N, Subraveti S G, et al. Harnessing the power of machine learning for carbon capture, utilisation, and storage (CCUS)–a state-of-the-art review [J]. Energy & Environmental Science, 2021, 14(12): 6122-6157.

[2] Sleiti A K, Al-Ammari W A, Vesely L, et al. Carbon dioxide transport pipeline systems: Overview of technical characteristics, safety, integrity and cost, and potential application of digital twin [J]. Journal of Energy Resources Technology, 2022, 144(9): 092106.

[3] CHEN J, LUO X, ZHANG H, HE L, CHEN J, SHI K. Experimental study on movement characteristics of bypass pig [J]. Journal of Natural Gas Science and Engineering, 2018, 59: 212-223.

[4] Acampora L, Grilletta S, Costa G. The Integration of Carbon Capture, Utilization, and Storage (CCUS) in Waste-to-Energy Plants: A Review [J]. Energies, 2025, 18(8): 1883.

[5] Lu H, Ma X, Huang K, et al. Carbon dioxide transport via pipelines: A systematic review [J]. Journal of Cleaner Production, 2020, 266: 121994.

[6] Lima P, Yeung H. Modelling of transient two-phase flow operations and offshore pigging; [C]. Proceedings of the SPE Annual Technical Conference and Exhibition, 2008.

[7] Oosterkamp A, Ramsen J. State-of-the-art overview of CO_2 pipeline transport with relevance to offshore pipelines [J]. Energies, 2008, 38(6):7.

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202603_12(3).0001

[8] Solghar A A, Davoudian M. Analysis of transient PIG motion in natural gaspipeline [J]. Mechanics & Industry, 2012, 13(5): 293-300.

[9] Ahmad M, Gersen S, Wilbers E. Solubility of Water in CO_2 Mixtures at Pipeline Operation Conditions [J]. Energies, 2014, 8(4): 262-267.

[10] Queimada A J, Zhang X, Pedrosa N, et al. Effect of Salts, Impurities, and Low Water Contents in the Formation of Gas Hydrates in CO_2-Rich Streams [J]. Journal of Chemical & Engineering Data, 2024, 69(10): 3284-3295.

[11] Bo S, LI T-y, Wei-qiang W. Transient numerical simulation of severe slugging in marine riser system [J]. Journal of Liaoning Shihua University, 2016, 36(03): 34-38.

[12] Jamshidi B, Sarkari M. Simulation of pigging dynamics in gas-liquid two-phase flow pipelines [J]. Journal of Natural Gas Science and Engineering, 2016, 32: 407-414.

[13] Tang, C., Chen, B., Qi, W., Zhao, Q., & Wang, X. (2024). Prediction of Hydrate Formation in Long-Distance Transportation Pipeline for Supercritical-Dense Phase CO_2 Containing Impurities. ACS omega, 9(50), 49728-49738.

[14] ON E. Transient analysis pigging pipeline [R]. Kingsnorth Carbon Capture & Storage Project, 2010.

[15] Skone T J. CO_2 Pipeline Pigging [R]. National Energy Technology Laboratory (NETL), Pittsburgh, PA, Morgantown, WV, and Albany, OR (United States), 2013.

[16] GL D. Design and operation of carbon dioxide pipeline [R]: DNVGL-RP-F104, 2021.

[17] SY/T 0533-1994. Technical Specification for Pig Design [S]. China National Petroleum Corporation, 1994.